

ISENTROPIC MELTING PROCESSES IN THE MANTLE

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Batch melting of ascending mantle can be approximated as an isentropic process, since on the time scale of melting heat flow into or out of source regions will typically be negligible and the process is slow enough to be close to reversible. Similarly, fractional fusion can be idealized as a series of incremental isentropic melting steps, although the entropy of the residue decreases in each step. Although actual melting processes (e.g., involving melt migration, diffusion, and convective boundary layers) must deviate to some extent from idealized isentropic conditions, modeling of mantle processes under the assumption of constant entropy is tractable from a thermodynamic perspective and leads to a number of insights. Here we present models of the productivity of isentropic pressure-release melting, consider the effect of solid-solid phase transitions on melting, and model deep crystal fractionation in ascending melts of the mantle.

Melt productivity

Decompression melting of the mantle is generally regarded as adiabatic, but rigorous modeling of this process has been handicapped by the lack of sufficiently detailed thermodynamic models of peridotite-liquid equilibria at high pressure. The MELTS package¹ is beginning to remedy this situation, and we have modified it to treat isentropic processes by minimization of enthalpy. Of particular interest is the melt productivity (percent melting per unit pressure drop) during polybaric melting. Although some successful models view melt productivity as constant or as an arbitrary function of depth², it is thermodynamically constrained, so models based on MELTS offer useful insights into its variations. Productivity is of great interest because it influences the thickness of crust that can be generated at a given potential temperature³ as well as the degree of depletion of the residuum as a function of depth⁴. In addition, non-uniform productivity as a function of depth would lead to non-uniform contributions to melt composition from different depth ranges and could influence significantly the fractionations of short-lived radioisotopes in magmas⁵. Heterogeneous melt production could also have a critical impact on melt transport and segregation⁶.

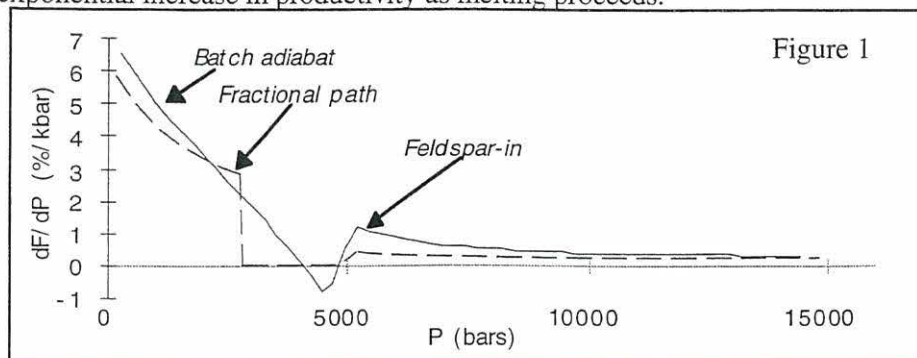
Because isentropic, polybaric, fractional melting experiments are not presently feasible, most previous estimates of productivity have been based on simple energy balance considerations that yield approximately constant values of melt productivity during ascent of fertile peridotite of 1–2 %/kbar^{4,7}. Melt productivity (per unit temperature change) during isobaric, fractional melting increases as melting proceeds in experiments⁸ and MELTS calculations⁹. This behavior is apparent in simple binary systems as well. Percent melting of peridotite along isentropic, polybaric paths based on MELTS calculations shows approximately exponential form, with low productivity near the solidus increasing to a maximum at the exhaustion of clinopyroxene^{9,10}. Analogy with

simple systems suggests that this is a general result for isentropic melting processes. Melt productivity functions of this form may require reexamination of many recent models in basalt petrology and geochemistry.

Phase Changes

Solid–solid phase changes in peridotite (e.g., garnet–to–spinel peridotite, spinel–to–plagioclase peridotite) lead to "cusps" in the solidus and are sometimes assumed to have an influence on melt productivity. In particular, it has been stated that near a solidus cusp, melt productivity will be enhanced compared to its value over pressure ranges in which solid–solid phase transitions do not occur^{11,12}. Simple entropy balance considerations require that solid–state phase changes affect melt productivity, but the sign of this effect depends on the entropy of the phase change. Both the garnet–spinel and spinel–plagioclase peridotite phase transitions have positive Clapeyron slopes; i.e., in both cases, the lower pressure assemblage has a higher molar entropy ("exothermic" transitions, in geodynamic usage). The formation of low-pressure phases therefore consumes entropy that would otherwise lead to melt generation. These phase transitions must, therefore, retard isentropic, decompression melting or even lead to freezing. There cannot be enhanced melting accompanying such phase transitions, even if there is a cusp in the solidus.

Model calculations in simple one–component and two–component systems demonstrate the effect of solid–solid phase transformations on isentropic decompression melting. The effect of solid–solid phase transitions on freezing is more pronounced for fractional fusion than for batch fusion; in particular, melting ceases for a finite pressure interval at pressures below the invariant point where melt and the solids involved in the phase transition coexist. Isentropic upwelling calculations for a model nine–component peridotite using MELTS verify that the simple–system behavior described in the previous paragraph can be extended to multicomponent, mantle–like systems: melt production during batch melting is greatly suppressed during the transformation from garnet–to–spinel peridotite and there is significant freezing during the transformation from spinel to plagioclase peridotite; during fractional fusion, barren zones are produced as in the simple systems. Figure 1 shows both a batch and a fractional melting path through the spinel–plagioclase transition. Note the interruption at the phase transition in the otherwise exponential increase in productivity as melting proceeds.



Low productivity phase transition regions have several potential implications for MORB petrogenesis. Quantitative evaluation of U–series

disequilibrium during basalt genesis requires that melting begin in the presence of garnet and that the rate of initial melt production be very low, which demands either that the upwelling rate or the melt productivity be very small during the initial stages of melting^{5,13}. Because previous models have assumed constant melt productivities of 1–2 %/kbar, they have required extremely small (0.01–1 cm/year) upwelling rates. Our results indicate, however, that productivity will be very small in the garnet–spinel transition zone, allowing generation of observed U–Th disequilibria at more reasonable upwelling rates.

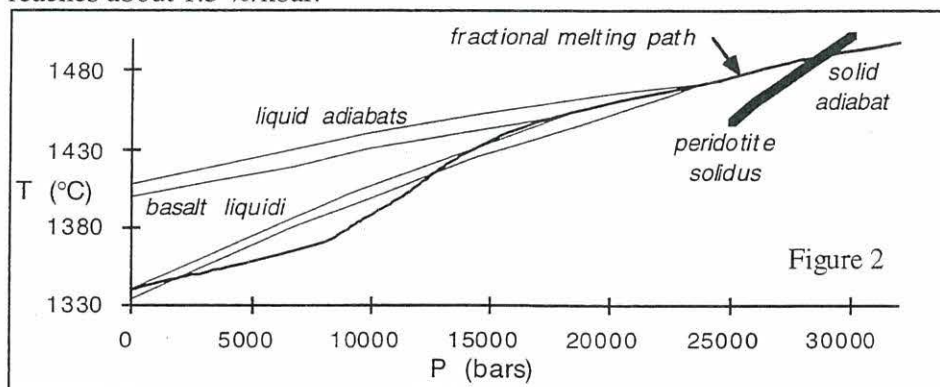
Freezing at the spinel–plagioclase transition could have implications for the role of plagioclase peridotite in melt generation from the oceanic mantle. The absence of large negative Eu anomalies in MORB¹⁴ has been taken as evidence that plagioclase does not form along normal adiabats in the oceanic mantle. Indeed, if the residue is too depleted by melting at deeper levels, plagioclase will probably not form in ascending peridotite at low pressure. However, if plagioclase ever did appear in the residue, this would shut off decompression melting for a finite depth range despite further upwelling, and could lead to a "lid" to melting at a depth of ~30 km. Hence along cold adiabats, it could be possible to produce primary plagioclase peridotite without the associated MORB showing evidence of residual plagioclase. Furthermore, the observations of enriched trace element patterns in plagioclase peridotites¹⁵ may be a signature of melt frozen in at a mid-ocean ridge as a result of the spinel–plagioclase transition rather than of later metasomatism.

Variations in melt productivity with depth in an upwelling mantle could affect the rate and mechanism of upward migration of melt. In particular, a region where melt-bearing mantle undergoes freezing or where productivity approaches zero during near-fractional melting could constitute a barrier to upward flow of melt from deeper in the melting regime. Accumulations of low-density melt would be unstable with respect to the overlying low-porosity zones, and we speculate that the unproductive zones would be breached episodically, likely in macroscopic conduits or high permeability zones. Increasing productivity as melting proceeds in upwelling mantle followed by freezing at a solid–solid phase transition could also lead to development of persistent conduits based on Spiegelman's⁵ demonstration that porosity waves in viscously deformable media nucleate where melt fraction increases along a flow path and grow in amplitude upon entering a region undergoing freezing, to the point where they could disrupt the matrix.

Crystallization of ascending liquids

During fractional melting, liquid segregates from the mantle over a range of depths. Numerous lines of evidence indicate that after separation from the residuum, ascending liquids do not significantly interact chemically with the surrounding mantle^{4,7}. The extent to which ascending liquids remain in thermal equilibrium with the surrounding mantle is less clear. If the "conduits" are thermally insulated, then ascending liquid will follow an adiabatic path ("liquid adiabat") that cools more slowly with decreasing pressure than the adiabatic path of the partially molten peridotitic country rock ("wet adiabat"). If, by contrast, the liquid equilibrates thermally with the walls of the conduits, then it follows the pressure–temperature path of the melting mantle. Kinzler et al.¹⁶

suggested that such cooling of the liquid would promote crystallization of olivine. It is intuitive that cooling a material initially at its liquidus must lead to crystallization, and there is evidence in MORB suites that has been interpreted to signify high-pressure crystal fractionation¹⁷. The MELTS calculations shown in Figure 2, however, demonstrate that the liquidus curves of basaltic liquids have positive slopes in P-T space that are actually steeper than the wet adiabat of peridotite under some conditions. In fact, these calculations predict that when the productivity of melting is low and the slope of the wet adiabat relatively shallow, fractional melts thermally equilibrated with the surrounding mantle will *not* crystallize on ascent. The same observation holds for accumulated fractional melts. As productivity increases during progressive melting, the wet adiabat steepens until eventually (near 5% total melting in the example shown), the liquidus curves of fractional melts become shallower in slope than the wet adiabat, and crystallization from ascending liquids is possible. These considerations place an upper limit on the depth at which fractional crystallization from basaltic liquids may take place in a given melting environment. In particular, they suggest that such crystallization is impossible at depths greater than those at which the productivity of fractional melting reaches about 1.5 %/kbar.



References

1. Ghiorso and Sack (1995) *Contrib. Mineral. Petrol.* **119**, 197-212.
2. McKenzie and O'Nions (1991) *J. Petrol.* **32**, 1021-1091.
3. McKenzie and Bickle (1988) *J. Petrol.* **29**, 625-679.
4. Plank and Langmuir (1992) *J. Geophys. Res.* **97**, 19749-19770; Johnson, Dick and Shimizu (1990) *J. Geophys. Res.* **95**, 2661-2678.
5. Beattie (1993) *Nature* **363**, 63-65.
6. Spiegelman (1993a) *J. Fluid Mech.* **247**, 17-38; Spiegelman (1993b) *J. Fluid Mech.* **247**, 39-63.
7. Langmuir, Klein and Plank (1992). AGU Geophys. Monogr. **71**, 183-280.
8. Hirose and Kawamura (1994) *Geophys. Res. Lett.* **21**, 2139-2142.
9. Hirschmann, Stolper, and Ghiorso (1994) *Min. Mag.* **58A**, 418-419.
10. Asimow, Hirschmann, Ghiorso, O'Hara and Stolper (1995) *Contrib. Mineral. Petrol.*, submitted.
11. Presnall, Dixon, O'Donnell and Dixon (1979) *J. Petrol.* **20**, 3-35.
12. Salters and Hart (1989) *Nature* **342**, 420-422.
13. Iwamori (1994) *Earth Planet. Sci. Lett.* **125**, 1-16; McKenzie (1985) *Earth Planet. Sci. Lett.* **72**, 149-157; Spiegelman and Elliott (1993) *Earth Planet. Sci. Lett.* **118**, 1-20.
14. BVSP (1981) *Basaltic Volcanism on the Terrestrial Planets*. Pergamon.
15. Dick and Bullen (1984). *Contrib. Mineral. Petrol.* **86**, 54-76.
16. Kinzler, Niu and Langmuir (1993) *EOS* **74**, 623 (abstr).
17. Grove, Kinzler and Bryan (1992). AGU Geophys. Monogr. **71**, 281-310.

PLUME 2

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